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TARSO – THE CORNER CONDITION OF TENSILE MEMBRANE ARCHITECTURE

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Summary: In order to promote the design of tensile membrane architecture and advance structural performance, interviews of experts are conducted and two case studies are discussed to serve as the foundation for developing a corner condition design framework. This paper introduces the term ‘tarso’ to identify and recognize the importance of the corner condition.

1 INTRODUCTION

The corner condition, hereinafter referred to as the ‘tarso’, plays a crucial role in the stability, functionality and aesthetic expression of tensile membrane architecture. While the importance of tarso has been acknowledged, there is a lack of design guidance or an evaluation framework for the design process. Currently, only general design principles exist in the literature [6, 8]. The responsibility for the corner detail design tends to belong to engineers or fabricators [16]. This can lead to a disconnection between tarso design and the overall architectural expression. Although a few generic corner detail solutions have been proposed and applied [4, 18], these “one-type-fits-all” solutions are questionable in meeting both the functional requirements and aesthetic expression of each unique tarso. Additionally, strategies for integrating tarso solutions into the architectural design process must still be refined. For these reasons, this research aims to propose a tarso design framework to improve tarso design and further strengthen and promote the application of the tensile membrane architecture.

The new term ‘tarso’ is described below, followed by a review of the available literature and guidelines in tarso design. Two case studies are presented with a focus on the interaction between the engineers and architects as a way to understand their involvement and the potential improvements of the process. A synthesis of expert interviews on the state of tarso design is presented, and the paper concludes with suggestions for the next steps towards establishing a framework.

2 TARSO

The lightweight, flexible nature of tensile membrane architecture offers vast possibilities for creating a spectrum of dynamically unique design forms. In addition to boundless visual expression, their dynamic qualities offer great potential for improving building performance[9]. However, due to varying load behaviors and anisotropic material properties, special engineering and architectural skills (i.e. form-finding, load analysis, and patterning) are needed to address the complexity of designing tensile membrane architecture. The detailing of the connections and joints is particularly critical because they essentially affect the entire structure's stability, durability, installation, maintenance, aesthetics and cost [7, 10].

As it stands, tarso design is often not central to the process; a muddy process of improvisation between the aesthetic and spatial interests of the architect and the structural responsibility of the engineer. The tarso warrants its own dedicated field of research. Design guidance, technologies and resources are not well developed or understood for the detailing of tensile membrane architecture. This is due in part to the inherent form-force consideration of dynamic behaviors in both membrane and boundary conditions, and to unique performance characteristics of each joint or connection specific to a project. As a result, developing a design guideline that can be systematically applied to address individual requirements is a challenge that needs to be further explored in order to broaden accessibility to tensile membrane architecture.

The connections and joints in tensile membrane architecture can be generally grouped into five categories: (1) surface-to-surface connections; (2) surface-to-edge connections; (3) corners; (4) field support connections; and (5) anchorages, as illustrated in Figure 1. Among all the connections, the corner detail is the most complex. First, it involves dramatic material property changes among different structural elements. The membrane, cables and (or) belts, come together in the corner assembly and must interact appropriately. Second, the corner detail is where forces are transferred from tension into compression. The detail must transfer and redirect high tension forces from a large surface area to a supporting structure. Lastly, its complexity is magnified by virtue of the fact that all these considerations must be resolved in the most concentrated area of the structure. The corner condition must consider the various factors and resolve them while maintaining the overall structural integrity and aesthetic. In order to better represent the importance and functionality of the corner condition, the term “tarso” is adopted as a more appropriate signifier.

Tarso is the Latin prefix form of “tarsus,” which refers to the tendon that attaches the eyelid allowing it to open or close [13, 19]. The term also translates to “ankle”; the seven bones composing the joint between the foot and leg utilize the same root signature [5, 20]. Just like the eyelid, which controls visual perceptions and communicates intent and emotion, the corner detail of tensile membrane architecture is part of the overall aesthetic expression and helps provide shape to the edge of the structure, defining how light is brought in. Like the human ankle, the corner detail is a major load-bearing joint. Similar to the eyelid and ankle's roles in human evolution, the corner detail is of vital significance in tensile membrane architecture and deserves its own field of study as such. Tarso study relates to the supporting, fastening, and tensioning of the tensile membrane in the corner connection area as well as the corner itself.

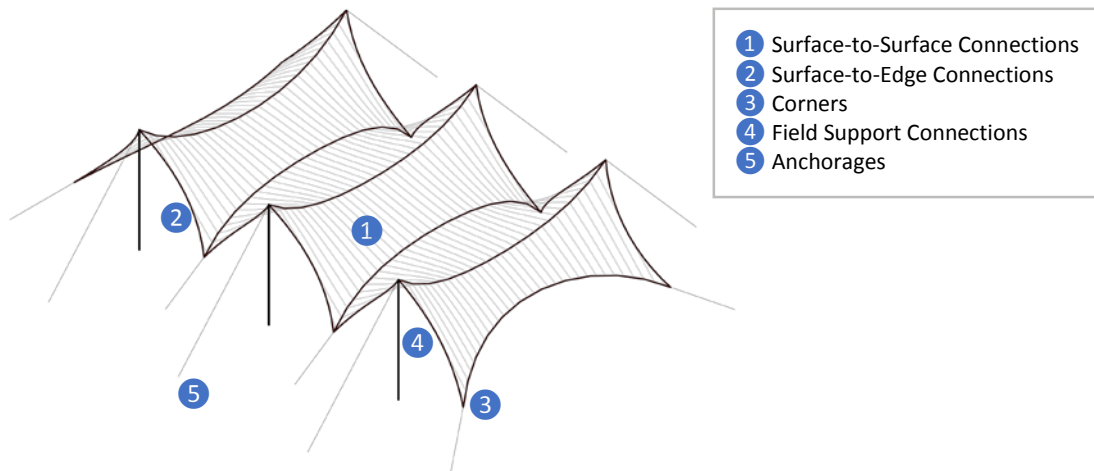


Figure 1: The connection categories in tensile membrane architecture.

3 PROBLEM DEFINITION & RESEARCH OBJECTIVE

During the last decade several efforts were made to establish structural detail vocabularies, develop a detail database, describing their usage on a case-by-case basis. Examples are the work of Bubner [3], the data bank of details and connections developed by Llorens and Irigoyen [11], and the detail collections of Péter and Dezső [14]. There have also been efforts to outline design criteria and principles to serve as design guidance for detailing tensile membrane architecture [6, 8, 10]. However, these resources remain inadequate to support the complex tarso design process. The rapid advancing of membrane technologies and materials, and the unique needs of each detail and connection make these resources of limited use. There is a serious lack of literature and research addressing the design process and collaboration means of the corner detailing. Many detailing tasks are done by engineers or fabricators based on their previous experience without paying special attention to the overall design aesthetic, spatial character and other architectural issues [15, 16]. As a result, much remains to be done in refining and developing connection details and the methods to design them. Based on the existing literature [6, 8, 10], the fundamental principles for designing tensile membrane connections can be summarized as follows:

1. Streamline Load Transfer: Connections must be able to resist, carry and transfer the required load densities, provide a smooth and direct load path, and prevent any eccentricities.
2. Displacement & Rotation Requirements: Connections should anticipate displacement and rotation as part of the resilience for the entire structure. In addition, they should also retain the required tension under expected movements to ensure the equilibrium of the form and force.
3. Adjustability for Pre-tension, Tension & Re-tension: The design of the connections needs to consider the pre-tensioning and tensioning mechanism during the installation process, as well as the adjustment for re-tensioning during the operation stage to maintain the tensile strength under long-term prestress.
4. Flexibility & Precision for Assembly: The design of the connection needs to take the

assembling methods and processes into account. Connections should be flexible enough to accommodate the required movement within the allowable space during the installation process to prevent any membrane damage or ruptures at installation. In addition, enabling high precision installation and avoiding human error are crucial since the final form of a tensile membrane structure is the result of precise form and force calculation.

5. **Durability:** Strength, stability and durability are basic structural requirements for all building systems. Where connections are exposed to weather and abusive environment, care must be taken in their detailing to avoid corrosion and deterioration. In addition, the point replacement mechanism needs to be thought through ahead without affecting the integrity of the entire structure if the membrane needs to be replaced in future.
6. **Aesthetic:** The appearance of the detail connections can be important. The visual elegance and expressiveness of exposed connections is critical to the aesthetic sensation of the structure. Lightness, simplicity, balance, and proper proportion are all part of the aesthetic quality that should be taken into account.

While the above mentioned principles encompass many of the criteria that should be taken into consideration during the detail design process, there are many reported failures of details, largely due to their failing in accordance with some of these principles [12]. A framework that effectively supports the consideration of the design principles can improve the quality of tarso design, and therefore improve tensile membrane architecture overall.

At the outset, the existing means and methods to consider these principles need to be understood. Working towards this goal, this research explores the existing means and methods for the tarso design by conducting expert interviews and case studies. The findings from these expert interviews and case studies will serve as part of the foundation for the future tarso design framework proposal.

4 TARSO DESIGN CASE STUDIES

4.1 Urban Loritz Platz, Vienna, 2000

Situated in the heart of Vienna, Austria, the roof structure at Urban Loritz Platz designed by Siljia Tillner of Architekten Tillner & Willinger ZT GmbH [2] was created to shelter commuters moving between buses, light rail transit and the underground train. The goal was to create an attractive space for travelers to make their connections without being affected by inclement weather. Its openness is a strategy to serve these multiple requirements within the various site constraints.

The structure has a 2,000 m² roof [17] and its design was a result of close collaboration between the architect and engineers. The engineering firm Schlaich Bergermann und Partner were chosen early in the process based on their prior experiences with membrane structures. The preliminary design was governed by the specific possible locations for the vertical support foundations. The limitations were due to the intersecting roadway and the light-rail platforms that were already in place. Once suitable foundation locations were determined, the structure

was form-found by rough sketches followed by 3D modeling, and executed with a combination of conical, truss, and hyperbolic shapes. The result is an undulating form that adequately covers the entire platform spanning to a walkway for passengers making a connection with the underground rail system.

The tarso design process was accomplished through an intricate partnership with the engineer. The architect would express her vision and the engineer would find a way to execute while providing guidance based on his expertise in tensile membrane structures. This open dialogue resulted in a structure that both the project architect and engineer, as well as the community and city officials are proud of.



Figure 2: Urban Loritz Platz full structure and connection detail. Images by the authors.

4.2 Dornerplatz, Vienna, 2005

The goal of the Dornerplatz structure was to reorganize a public space by bringing in shade in a way that would make an under-utilized plaza more enjoyable. The open plaza is located above a public parking garage that requires adequate access. Architekt DI Huber ZT-GmbH [1] designed a simple tensile membrane structure that offers shading while allowing the common areas to be freely accessible. Tensile membrane architecture was suitable because it offers shading in summer, and also withstands snow loads in winter. Since the firm does not specialize in tensile membrane architecture, it needed to acquire help from engineers and constructors. The resulting structure is a relatively simple form that was easy to erect.

The broader design concept was constrained by their unfamiliarity with tensile membrane architecture. The design is relatively straightforward -- a hyperbolic paraboloid. Based on prior knowledge, the architect understood this shape's ability to withstand wind and snow loads. The lack of design tools and the opportunity to closely collaborate with engineers was the defining reason to utilize this simple shape. The architect deferred to the engineer in creating the tarso. For the scope of this project, the aesthetic of the corner detail was not a defining element.

Building the Dornerplatz was dependent on spatial limitations and the expertise of the designers and contractors. Because the foundation was constrained by the parking garage below, the tensile membrane structure needed to be self-standing. Guy cables were not a likely option due to its proximity to the street. Therefore, a triangular truss was incorporated to provide adequate stability and serve as a design feature. There were two engineers: one who helped during the design phase with the corner detailing, and another engineer who was involved during the construction phase due to his prior experience working with the specific membrane

material.



Figure 3: Dornerplatz full structure and corner detail. Images by Architekt DI Huber ZT-GmbH and the author.

4.3 Summary of Case Studies

The tarso design and execution of these two cases exhibit the major challenge to tensile membrane architecture, and demonstrate how the challenge was addressed in different ways. The challenge is bringing multiple experts together to align goals for aesthetics, structural integrity, and construction. The success of the tarso relies on all of these factors being accounted for throughout the design and building process. The experts in both case studies stressed the importance of having an engineer involved during the design phase. This would ensure that what proposed would be buildable and safe. With the Urban Loritz Platz project, Architekten Tillner & Willinger and Schlaich Bergermann und Partner worked closely from the beginning of conceptual design to execution. This collaboration allowed the architect to take part during the detailing phase, allowing her to make aesthetic recommendations that she believed were important to maintaining the overall aesthetic expression of the structure. In contrast, the Dornerplatz project demonstrated how lack of design tools could limit design creativity, and how the tarso design fell solely to the responsibility of engineers. Both cases demonstrate that the level of tarso design knowledge impacted the architect's involvement during the process. The architects' unfamiliarity with tarso design left them to defer to the engineer.

5 TARSO DESIGN FRAMEWORK – SYNTHESIS OF EXPERT PERSPECTIVES

A series of semi-structured expert interviews were conducted to understand the existing design process and the needs for a tarso design framework. The sampling of the interviewees includes experts of various domains in tensile membrane architecture from Europe and North America. These experts include researchers, architects, engineers, contractors and manufacturers. In total, 17 experts were interviewed in Europe between April and May 2015. Additional interviews will be conducted in North America. The disciplines of the interviewees are summarized in Figure 4.

The interview questions were formulated by the authors and classified under five categories: background, design criteria, design methodology, evaluation methods, and potential solutions. The questionnaire probed the user's experience with tensile membrane architecture design, and specifically their experience in the tarso design. The questionnaire and the conversation was conducted by the authors with the following objectives:

- To identify the process for designing the corner condition
- To isolate impact factors that need to be considered
- To understand evaluation methods of a corner condition design
- To discover potential improvements for corner condition design process
- To isolate the knowledge architects need to be equipped for tensile membrane design
- To survey potential guidance available with current technology
- To propose an encompassing evaluation for corner condition design

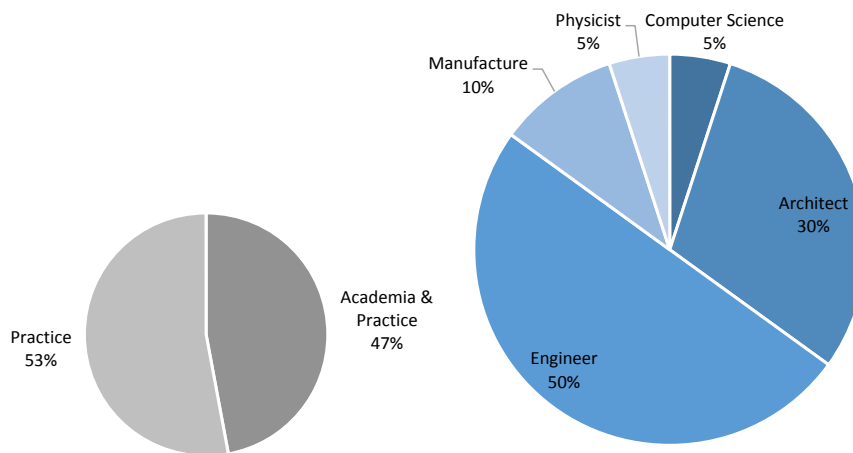


Figure 4: Field of disciplines of interviewed experts up until May 2015.

While the background information of these experts is the foundation for the validity of the gathered information, the interviewees will remain anonymous until final permissions are granted at the end of this research period. The following is a synthesis of the main findings from expert interviews that can serve as a basis for the tarso design framework.

1. Early Collaboration: Early design collaboration between architect and engineer is essential for the design of tensile membrane architecture. This was repeatedly emphasized by all the interviewees. Several interviewees stressed that the successes of

their projects were attributed to their early collaboration and a good working relationship between multiple team members. Regarding tarso design, there was no clearly recorded collaboration method between architects, engineers or fabricators, but each stated that some level of collaboration was crucial. The design of tarso was usually the sole responsibility of the engineers, and sometimes relied on the fabricator's input. However, participation from architects was highly recommended to maintain a homogenous aesthetic expression for the entire project. It was also mentioned that input from the architect's artistic viewpoint can push tarso design towards higher quality and might spark more creative and elegant solutions.

2. **Education:** Tensile membrane architecture is a very specialized field that is not the main focus of typical architectural training. Equipping new designers with basic knowledge such as form-force relationships, material behaviors, and the lightweight concept is fundamental to the early design process. The interviews identified a need for a short course to equip architects with basic understanding regarding the terminologies used, the principles of the form and force, and the anisotropic material behavior of textile membrane. If architects wish to be more deeply involved in the tarso design, knowledge of force diagrams and the mechanisms of specific connections must be acquired. Continuing education programs are suggested as a means to facilitate the process, but this is currently lacking in the academic curriculum. Engagement through interactive design software specifically for tensile membrane architecture was also cited as a potential learning medium. Sophisticated form-finding software is a potential means to facilitate this learning process.
3. **Force Diagram:** Building on the importance of specific knowledge, the understanding of the force diagram was pointed out as a crucial tool for the design of tensile membrane architecture. When asked about the required knowledge for architects for designing tensile membrane project, there is no indication of a need to master complex calculations and formulas. However, understanding the force diagram and the ability to use it as a communication tool is highly recommended. A simple and clear force diagram can be an effective way to communicate tensile membrane design among all parties.
4. **Design Guideline & Design library:** When asked about a potential guideline or standard for tarso design, concerns were raised regarding the potential limiting of creative innovation, however; general guidance was still recommended as a good starting point, especially for novices. In addition, the availability of the design libraries and examples of previous projects was cited as helpful for inspiring design ideas. The availability of previous lessons learned and some basic rules-of-thumb are also helpful to prevent repeating previous mistakes, and thereby increase design quality. Details regarding how guidance and prior examples will help while not stymieing design creativity need to be further refined by this research.
5. **Experience:** Practical experience is imperative to the success of designing and constructing tensile membrane architecture. In the engineering discipline, at least 4 years of post-graduate experience is recommended to gain the ability to manage tensile membrane design. Experienced manufacturers and contractors can reduce human errors and minimize logistical costs. As a result, it is important to team up with experienced partners to guarantee the success of a project. Special consultants for membrane

engineering, feasibility study or logistical planning are sometimes needed depending on the project size and the competency of the design team. While this might seem frustrating and become a limiting factor of the tensile membrane design, these knowledge and experience are accumulative and are essential to be considered no matter the project size or application.

6. **Adaptable Multi-Objective Design Support:** Depending on different project size and budget, the trade-off between the cost and quality is always an essential consideration during the design process. While architects and engineers might strive endlessly for the “ultimate” design, project time and budget are always limiting factors that must not be ignored. Design constraints need to be considered simultaneously, such as weather, site restrictions, durability, environmental performance, etc. More specifically for tarso design, one-fit-for-all solutions can minimize the cost of customization and are suitable for quick implementation, however; there are also cases that require highly customized tarso design. Therefore, a tarso design framework should be able to support considering multiple objective during the design process. In addition, it should be adaptable for varying design scenarios.

6 CONCLUSION

The objective is to develop a tarso design framework to advance the design process and improve the quality of tarso. The potential of tensile membrane architecture to improve building performance would positively influenced by better tarso design. If the tarso design process can be made more accessible, it can further promote the application of tensile membrane architecture. Initial findings from expert interviews and case studies have been synthesized here as a basis for the tarso design framework. Based on interviews with field experts, there is clear evidence that specialty knowledge and understanding has been established in the tensile membrane architecture field. Despite this, there is a lack of a central repository or methodology to synthesize data-rich information of one-off designs. It will be helpful to bridge existing knowledge and make it accessible for designers early in their design process. While it is unknown precisely how a framework might manifest itself, the growing capabilities of technology to streamline production and aid creativity presents great potential for integrating this guidance. The intent of this design framework is not to direct designers, but to facilitate and encourage the exploration of tensile membrane architecture.

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